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Characterization of Co-Fabricated Silicon TFT and MEMS Shutter Display

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Abstract

Active matrix shutter type displays consisting of thin film transistors and pre-stressed micro-electro-mechanical elements that were co-fabricated in simple and robust four or five mask processes exhibit a unique combination of attractive features such as excellent optical characteristics, fast switching time and outstanding operating temperature range.

Author Keywords

Active matrix; Micro-electro-mechanical-systems; MEMS; thin film transistor; TFT;

1. Introduction

Micro-electro-mechanical-systems (MEMS) can be used for implementing fast switching light shutters with outstanding high contrast ratios and optical throughput efficiencies. In the past, various reflective[1] and transmissive displays[2,3] have been reported that were built using conventional active matrix display technologies. In the past years, the Institute for Large Area Microelectronics (IGM) of the University of Stuttgart, Germany, has been demonstrating active matrix addressed arrays of vertically translating MEMS shutters, whose thin film transistors (TFTs) and vertically translating pre-stressed MEMS shutters were co-produced in a modified top-gate amorphous silicon process[4] using only four[5,6] or five[7] lithography masks.

2. Co-fabrication manufacturing processes

The co-fabrication process is based on the idea to use some of the nevertheless existing thin layers of the thin film transistor process for the realization of pre-stressed micro-electro-mechanical devices. This might include addition of specific sacrificial layers that are etched away to release the mechanical structures. In the previously reported IGM four mask co-fabrication process[5,6], the silicon nitride based gate dielectric and the gate metallization layers of a top-gate amorphous silicon process[4] are also used as the structural material of pre-stressed mechanical elements, which are released by selectively etching the amorphous silicon channel layer in the area of the MEMS device. Although the process is extremely simple, the performance of the realized MEMS shutters is compromised by the suboptimal mechanical and optical properties of the structural materials (silicon nitride and a molybdenum tantalum (MoTa) alloy. Figure 1 shows the principle of light modulation by the vertical movement of the MEMS elements. Without a driving voltage (relaxed state), the pre-stressed MEMS structure bends upwards and thus opens an aperture in the underlying counter electrode. This allows light from a diffused backlight to pass directly. Additionally, light reflected by the bottom electrode can still pass through the aperture after one or multiple reflections on the MEMS electrode and the bottom electrode. Minimizing the bending radius of the MEMS element will reduce its overlap with the physical aperture, thus increasing the effective light throughput. Unfortunately, for a given material set, a smaller bending radius also increases the activation voltage for the MEMS device. Applying this activation voltage pulls in the MEMS device by electrostatic force (collapsed state) and closes the aperture, thus blocking the passage of the light. To improve the overall shutter performance, an optimized process using an additional fifth mask for a dedicated sacrificial layer has been developed[6], which permits the use of more preferable chromium aluminum stack for the structural material of the MEMS device. In comparison to the original process, this yields a smaller bending radius without a penalty in activation voltage and improves the reflectivity of the MEMS element. Both effects lead to a significantly improved quite uniform light throughput (MEMS devices in the released state) of more than 30% on average (with peaks about 40%) for a highly diffuse backlight and a physical aperture of approximately 17%. Figure 2 shows the viewing angle dependent transmission characteristic.

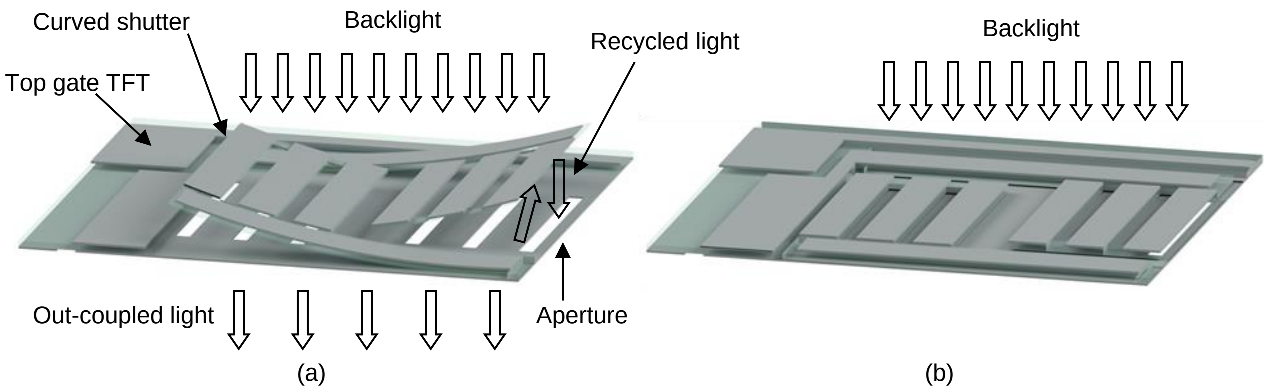

Figure 1. Concept of prestressed MEMS shutter (a) the curved shutter permits direct and recycled light transmission at its relaxed state (b) the shutter blocks light transmission at its collapsed state[7].

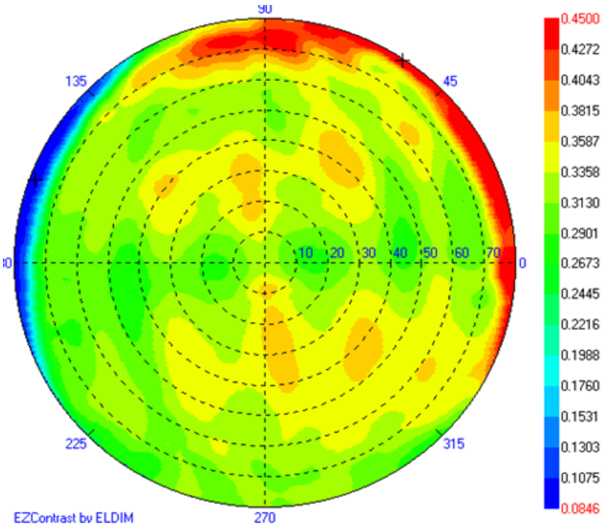

Figure 2. Transmission characteristic of shutters in released position[8].

3. Further Shutter Design Optimizations

Contrast Optimization

Measuring the contrast of the demonstrator yielded an unexpectedly low value of only 300:1, which clearly indicated a suboptimal dark state for the display. Careful investigation of the collapsed MEMS devices under a microscope (see Figure 3) indicated that the corners of the MEMS structure were still bend upwards, i.e. not lying flat on the bottom electrode, thus leading to some light leakage in this area.

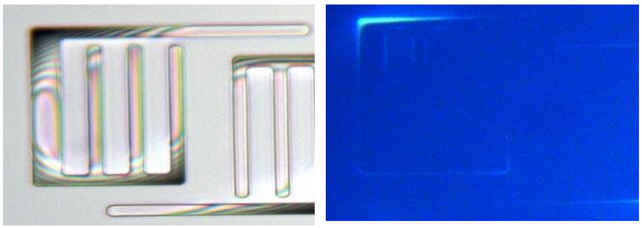

Figure 3. Microphoto of the illuminated shutters in collapsed position (left: top view, left bottom view, showing light leakage at the corners).

This issue was addressed by suitable changes in MEMS structure and processes, thus leading to an optimized device with a perfectly closed shutter (see left of Figure 4).

Figure 4. Microphoto of bottom view of the optimized illuminated shutters (left: collapsed shutter, right: released shutter).

Using the measurement equipment currently available at our institute, the luminance in the collapsed state was below the measurement limit, so that we can safely state that the contrast is well (probably orders of magnitude) higher than 1000:1.

Operating Temperature Range

The principle of operation of the shutter display only requires a suitably pre-stressed MEMS structure. This is a profound difference to liquid crystal displays electro optic effects, whose operating temperature range might be significantly more limited. To verify high temperature operation of the active matrix MEMS displays, actual active matrix MEMS display demonstrators were placed on a hotplate (see Figure 5).

Figure 5. Active matrix MEMS shutter demonstrator testing on a hotplate.

The experiments demonstrated correct switching operation in the entire tested temperature range from 80°C to 140°C. So far, water vapor in the ambient air inside the glass package is expected to limit the low temperature operation to temperatures above the freezing point. Dry air packaging or vacuum packaging are currently under investigation to solve this issue.

Switching Time Optimization

In comparison to many liquid crystal modes, the quite high stress density in the MEMS structures offer the possibility for relatively fast switching. Sub-millisecond response times are highly desirable as they would be indispensable for field-sequential color systems. Previously, we reported a surprisingly strong asymmetry of the switching behavior of directly addressed MEMS devices[8]. Those experiments demonstrated a collapse response time in the range of 500 µs and release times in the range of tens of milliseconds.

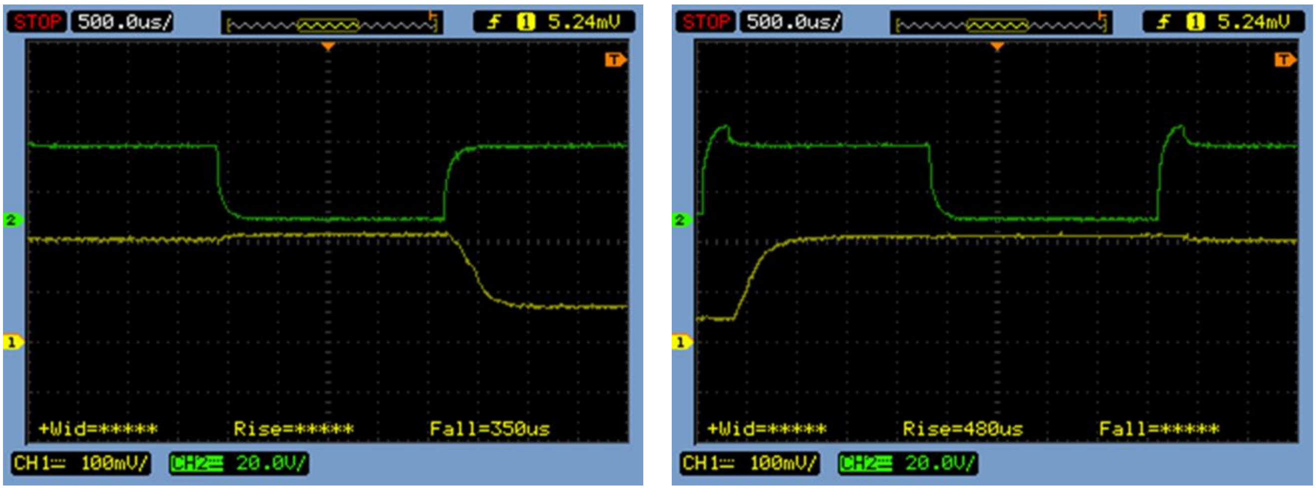

Figure 6. Oscillogram showing response time of DC free driven MEMS shutters (Left: Transition from released to collapsed, Right: Transition from collapsed to released). The green signal at the top is the electrical control signal and the yellow signal at the bottom shows the output signal of a photodiode used for measuring the optical response.

Closer investigation showed that this highly undesirable asymmetry was caused by unintended charging of the MEMS structures. DC free addressing (like in liquid crystal displays) led to a significant improvement allowing for response times in the range of 400 µs in both switching directions (see Figure 6 for an actual oscillogram of this experiment). Further dampening effects of surface forces (e.g van der Waals forces) and humidity are currently under investigation. Nevertheless, it is obvious, that the so far achieved switching times are already very suitable for implementing field sequential color schemes.

4. Improved AM-MEMS Shutter Demonstrator

Using the optimized five mask manufacturing process, an initial 1.45 cm diagonal active matrix demonstrator with 48x72 pixels, each containing one amorphous silicon addressing TFT (W/L=20µm/5µm) in the pixel area of 220µm x 130 µm, had previously been demonstrated[8]. Figure 7 shows a new 6 cm diagonal AM-MEMS display demonstrator having 320x240 pixels of 150µm x 150µm each. The currently used simplified driving system applies the signals to connected neighboring row and column lines, thus allowing to demonstrate varying checkerboard patterns with pulse width modulation based gray scales.

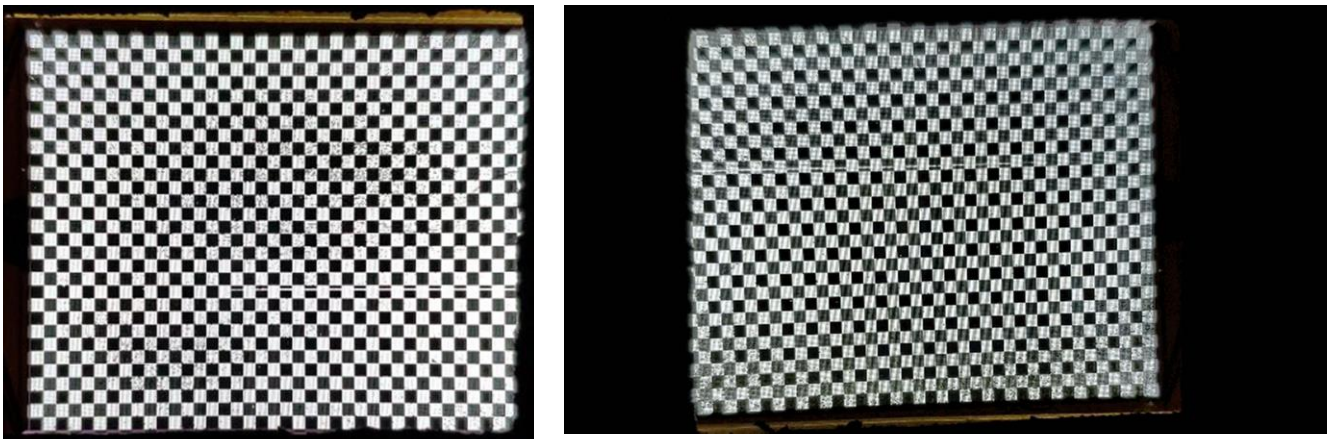

Figure 7. 6cm diagonal AM-MEMS shutter display demonstrator depicting simple checkerboard patterns (Left: Black and white pattern, Right: Pattern where the dark blocks in every second row are gray instead of black).

5. Conclusions

Major improvements of an AM-MEMS shutter display technology have been presented. Optimization of the MEMS process and overall structure significantly increased the contrast. Additionally, modifications in the driving circuit resulted in nearly symmetric fast response times, which are an essential prerequisite for future field sequential color systems.

Another unique advantage is the outstanding operating temperature range. So far, correct operation has been demonstrated up to 140°C. The improved robustness and maturity of all involved manufacturing processes has been shown by a larger and higher resolution AM-MEMS shutter display demonstrator. Integration of the MEMS shutters with faster switching TFT Technologies such as low temperature polysilicon (LTPS) or indium gallium zinc oxide (IGZO) as well as vacuum packaging for increased operating temperature range in sub-freezing temperatures and even faster response times are currently under investigation and will be reported in the future.

6. References

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